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USAAVLABS TECHNICAL NOTE 1

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U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

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37

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ABSTRACT

Crack arrest and residual static strength tests were conducted on 12-inch-wide bare and clad 7075-T6 aluminum alloy specimens to determine the effects of thin straps of fiberglass tape bonded to the specimens. Specimens were preloaded in a close-loop hydraulic test machine, a pointed 0.375-inch-diameter rod was driven through their midpoint, and their crack arrest and residual static strength behavior was observed with high-speed photography. Various configurations were studied, including those with one strap bonded to one side of the specimen and those with two straps bonded to either one or both sides of the specimen. The tests indicated that running cracks can be arrested by the fiberglass straps. Significant increases in the crack arrest behavior of up to 48 percent were obtained with two 0.75-inch by 0.010-inch straps spaced 2.75 inches apart on the front and back sides of the specimen. Residual static strength values (for a specimen with a 2-inch-long crack) approaching the ultimate tensile strength of the material were achieved by this method.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure		Page

INTRODUCTION

Catastrophic failures in aircraft have focused attention on the problem of developing techniques to improve the residual static strength of parts containing cracks. In the case of military aircraft, single-shot kills have occurred as the result of ballistic impact on stressed skin panels. In particular, high-strength aluminum alloys such as 7075-T6, which is currently being used, are particularly susceptible to catastrophic failure.

In reviewing the knowledge of fracture mechanics, it appears that the plastic zone is usually of fairly small diameter. This is "where the action is." While the stress intensity within such a zone is quite large, the dimensions of the zone are rather small; thus, the load that is transmitted across the zone is moderate. The method of crack arrest presented here is derived from the concept that if a fiber could be placed across the plastic zone and normal to the line of the crack, the moderate load at that discretely fine volume would be divided between the fiber and the metal substrate, thus reducing the stress intensity to a level below that required to propagate the crack. A thin layer of fiberglass is bonded in close proximity to the plate. This layer, while carrying only a small portion of the applied load, is sufficient to carry a large portion of the load across the plastic zone. Either complete sheathing of the metal or straps bonded to the metal may be used effectively.

The purpose of this investigation was to determine the effect of thin straps of fiberglass on the crack arrest and residual static strength behavior of 7075-T6 aluminum panels. Stressed panels were subjected to impact loading by driving a pointed 0.375-inch-diameter rod through their midpoint.

MATERIALS AND SPECIMEN PREPARATION

The materials studied in this investigation included 7075-T6 bare and clad aluminum alloys. The specimens were 0.032 inch thick, 12 inches wide, and 20.5 inches long (free length between grips).

All specimens were tested in the as-received condition. The grain direction was parallel to the direction of loading. The tensile properties of the 7075-T6 alloy were obtained from standard ASTM tensile specimens and are given in Table I; each value presented is the average value of three specimens.

Details of the 1002-S prepreg fiberglass used for straps are also presented in Table I. The straps were bonded to the specimen and terminated at the grips. The prepreg straps were applied to the specimens using the following procedure:

1. The specimen was cleaned with acetone.
2. The specimen was lightly ground in the strap bond area with 100 grit paper parallel to the direction of loading (see Figure 1a).
3. The specimen was cleaned with acetone.
4. (a) The specimen was cleaned with alcohol (specimens 1 through 15 only).

   (b) The specimen was etched with a sodium dichromate (10 parts)/sulfuric acid (100 parts)/distilled water (300 parts) bath (specimens 16 through 32) (see Figure 1b).
5. The specimen was washed with distilled water.
6. The specimen was dried with a heat lamp.
7. Masking tape (14 mil thick for specimens 1 through 22 and 7 mil thick for specimens 23 through 32) was applied in the non-bond area, leaving a gap of approximately 1/8 inch on each side to allow for expansion of the fiberglass strap when pressed. The masking tape prevented excessive fiber wash and allowed for overflow of excess resin (see Figure 1c).

8. An 8- to 10-mil thickness of Epon 828 resin with Z curing agent was applied to the bond area.

9. A single layer of 1002-S unidirectional prepreg tape was placed parallel to the direction of loading (see Figure 1d).

10. The tape was rolled with a roller to remove entrapped air.

11. The specimen was vacuum-bagged (specimens 1 through 24).

12. Vacuum was applied (specimens 1 through 24).

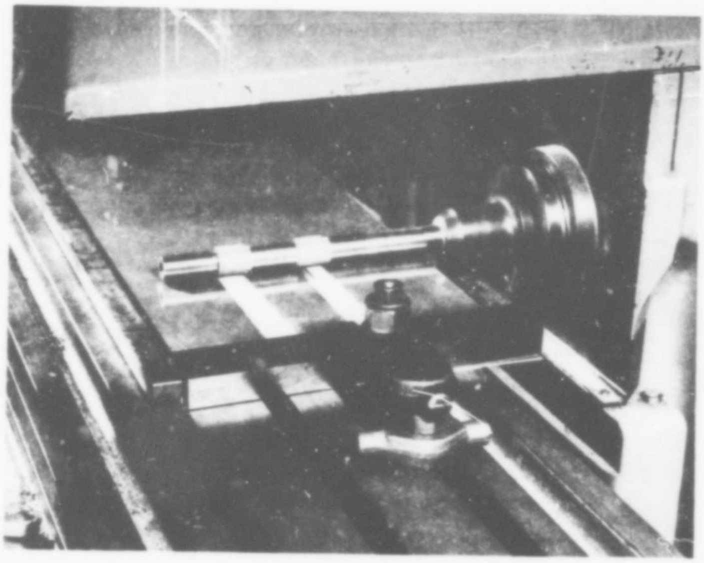
13. The specimen was placed in a press at 30 psi, 330°F, for 1 hour (see Figure 1e).

14. The specimen was postcured in an air circulating oven at 280°F for 1 hour (see Figure 1f for finished specimen).

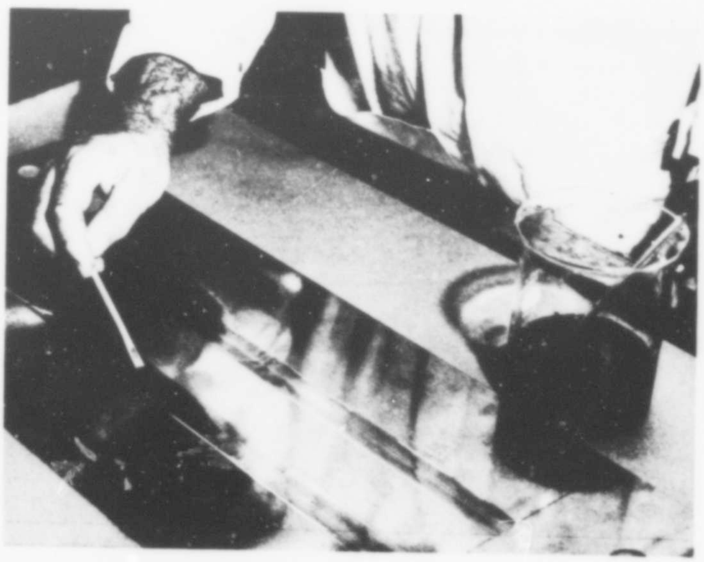
TABLE I. TENSILE PROPERTIES OF MATERIALS TESTED

Material	Ultimate Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation (1-in. Gage Length) (pct)	Elongation (2-in. Gage Length) (pct)	Modulus (ksi)
7075-T6 Clad	73.9	67.7	9.3	13.3	10.2×10^3
7075-T6 Bare	77.3	70.3	10.0	11.3	10.2×10^3
1002-S Prepreg*	195.0	-	-	-	6.4×10^3

*3M Company Data.

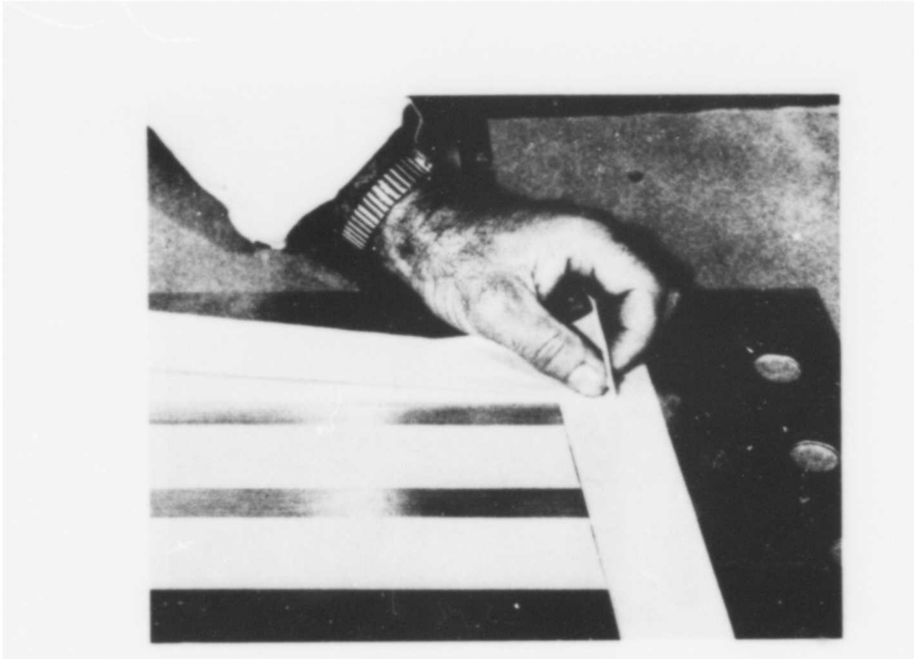


a. Grinding Operation.

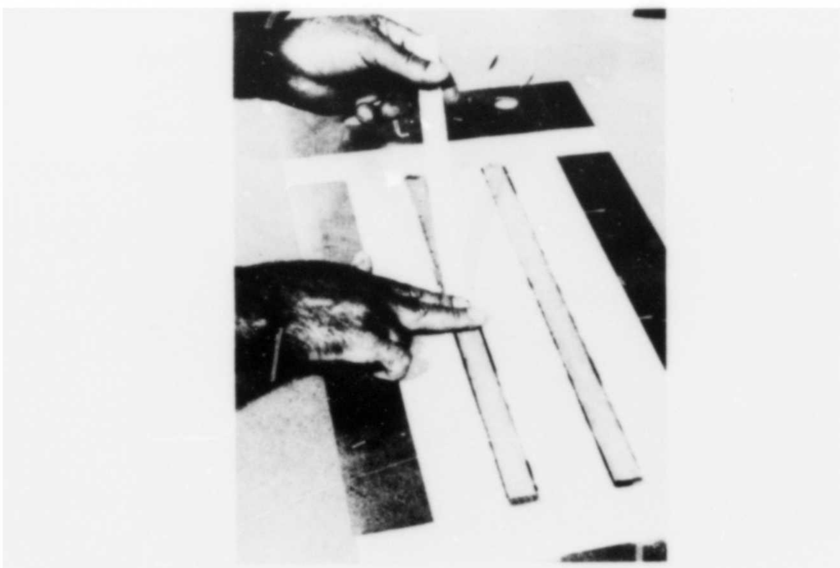


b. Acid Etching.

Figure 1. Specimen Preparation.



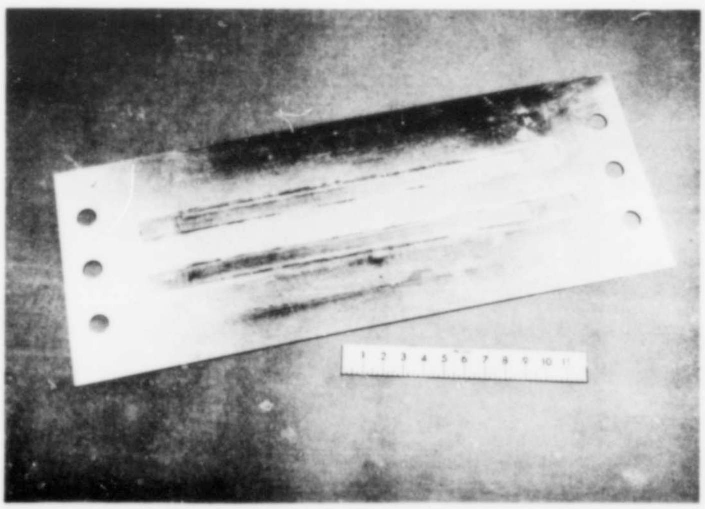
c. Taping Procedure.



d. Laying of Fiberglass Straps.

Figure 1. Continued.

e. Pressing Operation.



f. Finished Specimen.

Figure 1. Continued.

EQUIPMENT AND TEST PROCEDURE

A 100,000-pound-capacity close-loop hydraulic test machine was used to perform the static tests. Loads were monitored with a Brush recorder, a recording oscilloscope, and an X-Y plotter. The specimens were loaded to predetermined values, and a pointed 0.375-inch-diameter steel rod was driven through the specimen midpoint with the pendulum device shown in Figure 2. A point was ground on the rod simulating that of a .38 caliber bullet (see Figure 3). Projectile impact velocities of 15.1 feet per second were obtained from measurements taken from motion picture film shot at 720 frames per second. The pendulum stayed in contact with the pointed rod during the time that the rod was being driven through the specimen.

An 8mm camera operating at 10,000 frames per second was used to obtain crack growth data. In cases where failure did not occur on impact, the load was removed, the crack length was measured, and the specimen was reloaded to failure at a load rate of 1000 pounds per second.

Stresses quoted herein were calculated using the net specimen area plus the strap area.

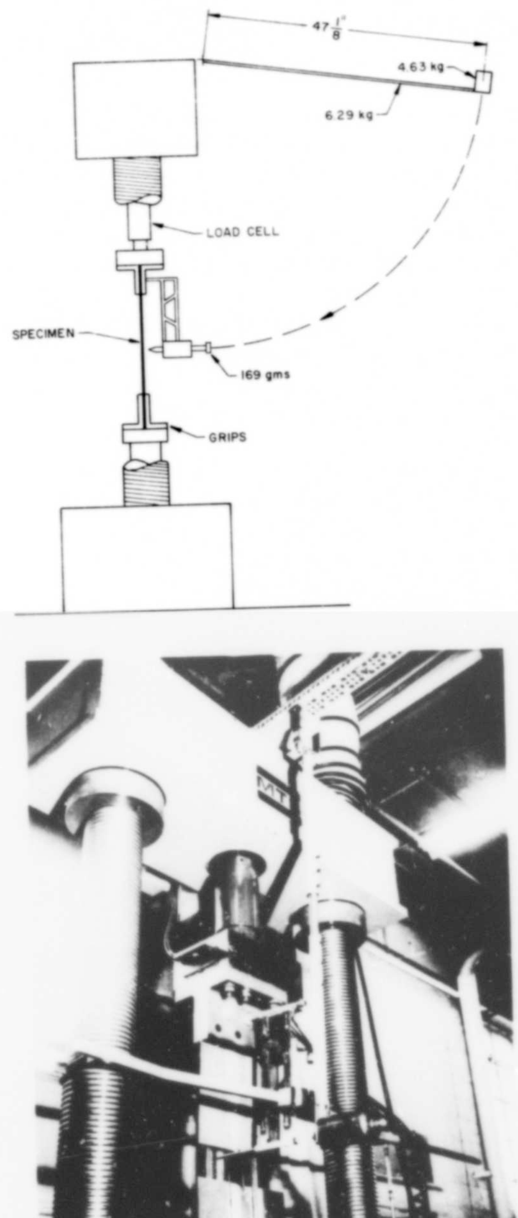


Figure 2. Test Setup.

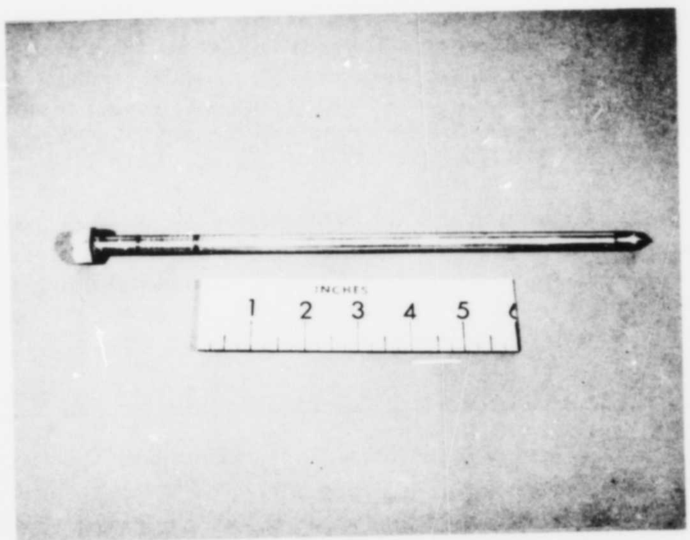


Figure 3. Projectile Used in Impact Tests.

RESULTS

7075-T6 BARE AND CLAD, NO STRAPS

Figure 4 presents the results of the tests conducted to establish the threshold stress, i. e. , the stress above which projectile impact would produce catastrophic failure. The numbers in Figure 4 correspond to the specimen numbers in Table II.

A typical crack in an unstressed specimen resulting from the impact test is shown in Figure 5. It is interesting to note that the resulting crack lengths (in the panels that were stressed) varied as a function of the initial value of stress, with the lower values of stress resulting in the longer crack lengths. Based on the data from the impact tests, a value of 36 ksi was chosen as the threshold stress for both the bare and the clad material.

The residual static strength values, which were obtained by loading to failure those specimens that did not fail on impact, agree closely with published data on 12-inch-wide 7075-T6 specimens containing fatigue cracks.* A curve was faired through the residual static strength data for use in later comparisons with panels containing straps.

7075-T6 CLAD, STRAPS ON FRONT AND BACK SIDES OF SPECIMEN

Test data for 7075-T6 clad material with straps on both the front and back sides of the specimen are presented in Figure 6. In this portion of the study, both the spacing and the number of straps varied (see Table II).

Specimen 10 was the only specimen that did not fail when subjected to impact at a stress above the threshold stress. The resulting crack length was 1. 25 inches. During the residual static strength test of specimen 10, the load reached a point where the crack began to run catastrophically; however, when the crack (approximately 3. 10 inches in length) reached the straps, it was arrested. The net section stress at this point was 57. 0 ksi. The load was increased until the crack growth reinitiated and failure occurred.

*Paul Kuhn and I. E. Figge, Sr. , UNIFIED NOTCH STRENGTH ANALYSIS FOR WROUGHT ALUMINUM ALLOYS, TN 1259, National Aeronautics and Space Administration, Washington, D. C. , 1962.

The open symbol for test 10 represents the net section stress at failure and was based on the initial crack length of 1.25 inches. The solid symbol represents the crack length and net section stress level at which crack arrest occurred. With the exception of specimen 10, there was essentially no improvement in the crack arrest or residual static strength behavior. However, because of the limited number of tests on the clad material, the results are somewhat inconclusive. Also, based on the results of later tests, the cleaning procedure may have had a detrimental effect on the results.

7075-T6 BARE, TWO STRAPS ON FRONT AND BACK SIDES OF SPECIMEN

Test data on 7075-T6 bare material with two straps (0.75 inch by 0.010 inch) on both the front and back sides of the specimen are presented in Figure 7. Strap spacings of either 2.75 or 3.75 inches (centerline to centerline) were used.

In specimens 13 and 15, the cracks ran partially under the straps upon impact and stopped; the specimens held the load for 2.5 and 6 seconds, respectively, and then failed. Examination of these specimens indicated a poor bond that was probably caused by a thin film of acetone that was still visible on the surface of the specimens. A revised cleaning procedure was used to eliminate the film (see step 4b under Materials and Specimen Preparation).

The highest crack arrest values for the 2.75- and 3.75-inch spacings were 53.2 ksi (specimen 18) and 42 ksi (specimen 11), respectively. Typical crack arrest behavior is shown in Figure 8. The residual static strength values of these specimens were 71.4 ksi and 62 ksi, respectively. The value of 71.4 ksi approaches the ultimate tensile strength (77.3 ksi) of the 7075-T6 alloy. The crack arrest value for specimen 18 was approximately 48 percent higher than the threshold stress. The residual static strength for this specimen was approximately 70 percent higher than that for panels with no straps and 62 percent higher than that for panels with riveted aluminum stiffeners (unpublished NASA data).

7075-T6 BARE, TWO STRAPS ON IMPACT SIDE OF SPECIMEN

Test data on 7075-T6 bare material with two straps (0.75 inch by 0.010 inch) on the impact side of the specimen are presented in Figure 9. In general, the crack arrest and residual strength behavior with two straps on the impact side of the specimen was not as good as that obtained with two straps on both sides of the specimen. Crack arrest values 15 percent higher than the threshold were obtained for specimens with straps on the impact side, as compared to 48 percent higher for specimens with straps on both sides. Residual static strength values for specimens with straps on the impact side were 46 percent higher than those for specimens with no straps, as compared to 70 percent higher for specimens with straps on both sides.

One interesting fact (observed from the films) that probably contributed to the lower strengths of the specimens with straps on the impact side was that on impact the sheet material was displaced out of plane (away from the straps), whereas the straps tended to stay in their original plane. This behavior caused a local debonding of the straps in the vicinity of the impact point and thus reduced the effectiveness of the straps as crack arrestors (see Figure 10). Only a very slight amount of debonding occurred in the specimens with straps on both sides. In all cases where failure occurred, the sheet material completely failed first, followed by the strap bond failing in shear.

7075-T6 BARE, ONE WIDE STRAP ON IMPACT SIDE OF SPECIMEN

Test data on 7075-T6 bare material with one strap centrally located on the impact side of the specimen are presented in Figure 11. Straps with widths of 3, 4, and 7 inches were tested. As in the previous case, some local debonding of the straps occurred on impact. Fiber delamination was essentially circular in shape (see Figure 12) and in general was approximately 0.20 inch larger in diameter than the crack in the aluminum panel. Only one test was conducted with a 4-inch-wide strap (specimen 24). This specimen, preloaded to 50 ksi, did not fail on impact. In this particular case, no horizontal crack growth occurred on impact (see Figure 13). A residual static strength test was not conducted on this specimen. The threshold stress for specimens with 3-inch-wide straps was estimated at approximately 43 ksi, which is 19 percent higher than that for specimens with no straps. The threshold stress for specimens with 7-inch-wide straps was estimated at 50 ksi, which is 39 percent higher than that for specimens with no straps. Increases in residual static strength of up to 33 percent were obtained with the 7-inch-wide straps.

TABLE II. CRACK ARREST AND RESIDUAL STATIC STRENGTH BEHAVIOR OF MATERIALS TESTED

Specimen No.	Specimen Matl	Specimen Width (in.)	Specimen Thickness (in.)	Strap Matl	Strap Width (in.)	Strap Thickness (in.)	Strap Spacing (in.)	Static Load (lb)	Static Stress (ksi)	Failure Mode	Resulting Crack Length (in.)	Failure Load (lb)	Failure Stress, Net Section (ksi)	Remarks
A	7075-T6 Clad	12	0.032	None	-	-	-	-	-	-	3.00 (Sawcut)	11,000	38.3	
B					-	-	-	0	0	Did Not Fail	1.00	16,200	46.0	
C					-	-	-	0	0	Did Not Fail	2.00	13,850	43.3	
1					-	-	-	15,000	39.1	Rapid Fracture	-	-	-	
2					-	-	-	14,000	36.5	Rapid Fracture	-	-	-	
3					-	-	-	12,000	31.3	Did Not Fail	2.63	12,200	40.7	
4					-	-	-	12,500	32.5	Did Not Fail	1.88	14,300	43.5	
5					-	-	-	13,420	35.0	Did Not Fail	1.56	15,600	46.5	
6					-	-	-	15,000	39.1	Rapid Fracture	-	-	-	
7				3M Glass Tape	1.00	0.007	4 Pieces, Left Side, One Side of Specimen	15,000	39.1	Rapid Fracture	-	-	-	
8				3M Glass Tape	1.00	0.007	6 Pieces, Front and Back Sides, S = 1.75*	15,000	32.0	Did Not Fail	2.00	17,400	43.0	
9				1002-S	0.75	0.010	6 Pieces, Front and Back Sides, S = 1.75*	16,000	33.8	Did Not Fail	0.69	25,500	56.3	Failed in Grips
10					0.75	0.010	2 Pieces, Front and Back Sides, S = 3.75	15,500	37.5	Did Not Fail	1.25	19,800	53.0	Crack Arrested @ Strap @Crack Length = 3.35 in., S_n = 57.0 ksi
11	7075-T6 Bare	12	0.032		0.75	0.010	2 Pieces, Front and Back Sides, S = 3.75	17,400	42.0	Did Not Fail	3.10	19,500	62.0	
12				None	-	-	-	15,500	40.3	Rapid Fracture	-	-	-	
13				1009-S	0.75	0.0075	2 Pieces, Front and Back Sides, S = 3.75	16,300	40.0	Crack Arrested at Straps, Load Increased, Rapid Fracture	4.80 When Crack Arrested	16,300	64.0	Spec Failed About 2.5 Sec After Impact

*Center Straps. Remaining Straps S ≈ 2.5 in.

TABLE II - Continued

Specimen No.	Specimen Matl	Specimen Width (in.)	Specimen Thickness (in.)	Strap Matl	Strap Width (in.)	Strap Thickness (in.)	Strap Spacing (in.)	Static Load (lb)	Static Stress (ksi)	Failure Mode	Resulting Crack Length (in.)	Failure Load (lb)	Failure Stress, Net Section (ksi)	Remarks
14	7075-T6 Bare	12	0.032	1002-S	0.75	0.010	2 Pieces, Front and Back Sides, S = 2.75	19,200	46.4	Did Not Fail	2.05	23,815	68.6	Poor Bond
15							2 Pieces, Front and Back Sides, S = 2.75	20,700	50.0	Crack Arrested at Straps, Held Load 6 Sec, Straps Failed in Shear, Spec Failed	2.85, Estimated	20,700	64.1	Spec Improperly Cured at 525°F
16							2 Pieces, Front and Back Sides, S = 2.75	21,900	53.0	Did Not Fail	2.05	24,600	70.7	Revised Cleaning Procedure Used for Specimens 16 - 32
17							2 Pieces, Front and Back Sides, S = 2.75	23,000	55.6	Fracture	-	-	-	Crack Slowed Slightly in Region of Straps
18							2 Pieces, Front and Back Sides, S = 2.75	22,000	53.2	Did Not Fail	2.13	24,600	71.4	
19							2 Pieces, Impact Side, S = 2.75	17,900	45.0	Rapid Fracture	-	-	-	Extremely Poor Bond Improperly Cleaned
20							2 Pieces, Impact Side, S = 2.75	15,900	40.0	Rapid Fracture	-	-	-	Poor Bond Improperly Cleaned
21							2 Pieces, Impact Side, S = 2.75	15,900	40.0	Did Not Fail	2.46	17,750	55.5	
22							2 Pieces, Impact Side, S = 2.75	17,000	42.6	Rapid Fracture	-	-	-	
23							2 Pieces, Impact Side, S = 2.75	16,500	41.4	Did Not Fail	2.75	17,800	57.2	
24					4.00		1 Piece, Impact Side	21,200	50.0	Did Not Fail	0.95	Not Tested	-	No Horizontal Crack Growth

TABLE II - Continued

Speci-men No.	Speci-men Matl	Speci-men Width (in.)	Speci-men Thick-ness (in.)	Strap Matl	Strap Width (in.)	Strap Thick-ness (in.)	Strap Spacing (in.)	Static Load (lb)	Static Stress[g] (ksi)	Failure Mode	Resulting Crack Length (in.)	Failure Load (lb)	Failure Stress, Net Section (ksi)	Remarks
25	7075-T6 Bare	12	0.032	1002-S	3.00	0.010	1 Piece, Impact Side	18,600	45.0	Crack Arrested, Held Load 3 Sec, Specimen Failed	1.90, Estimated	18,600	49.1	
26					3.00		1 Piece, Impact Side	23,000	55.5	Rapid Fracture	-	-	-	
27					3.00		1 Piece, Impact Side	22,000	53.2	Rapid Fracture	-	-	-	No Resin Used
28					7.00		1 Piece, Impact Side	21,800	48.0	Did Not Fail	2.00	25,600	65.7	2.25-in. Fiber Delamination
29					6.50		1 Piece, Impact Side	19,000	42.3	Did Not Fail	1.45	25,000	62.0	1.65-in. Fiber Delamination
30				None	-	-	-	17,000	44.2	Rapid Fracture	-	-	-	
31				1002-S	7.00	0.010	1 Piece, Impact Side	18,000	39.6	Did Not Fail	1.10	28,000	69.4	1.20-in. Fiber Delamination
32					7.00	0.010	1 Piece, Impact Side	24,000	53.0	Rapid Fracture	-	-	-	

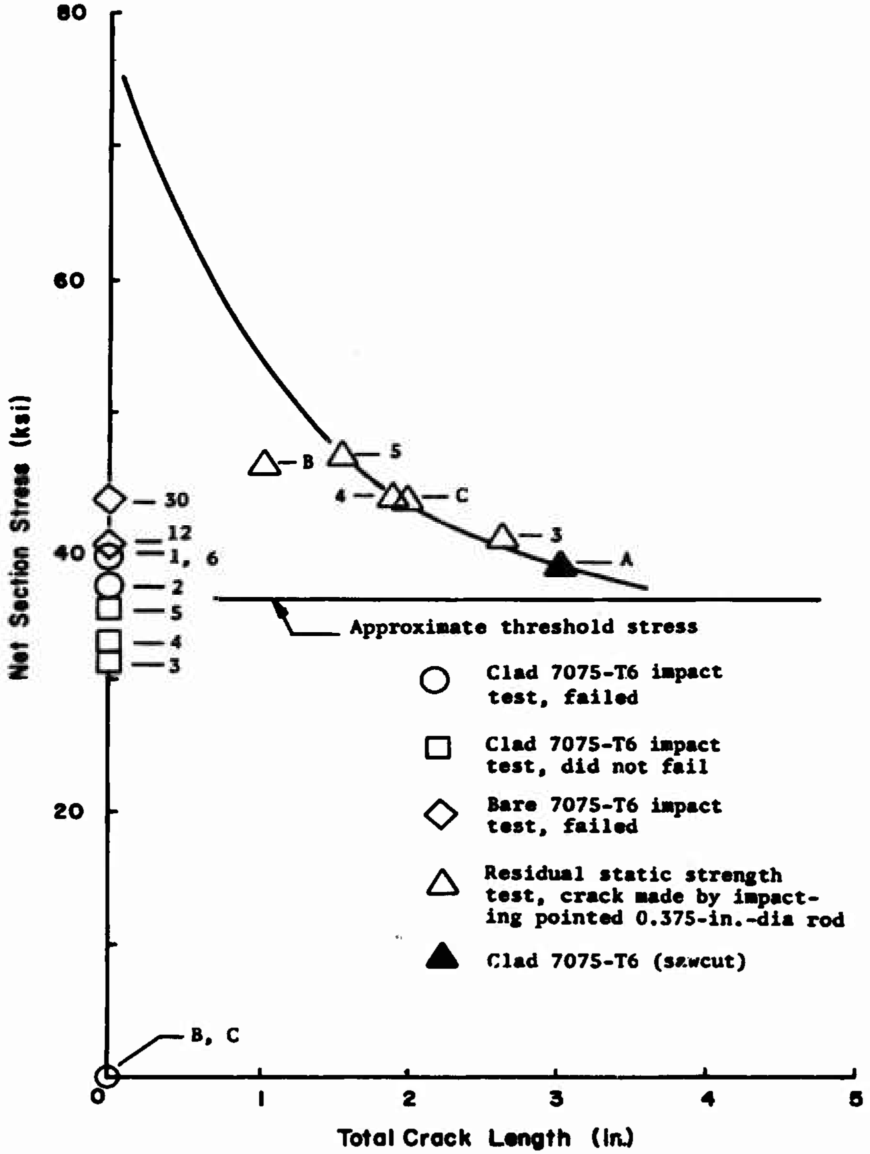


Figure 4. Crack Arrest and Residual Static Strength of 12-Inch by 0. 032-Inch 7075-T6 Panels Without Straps.

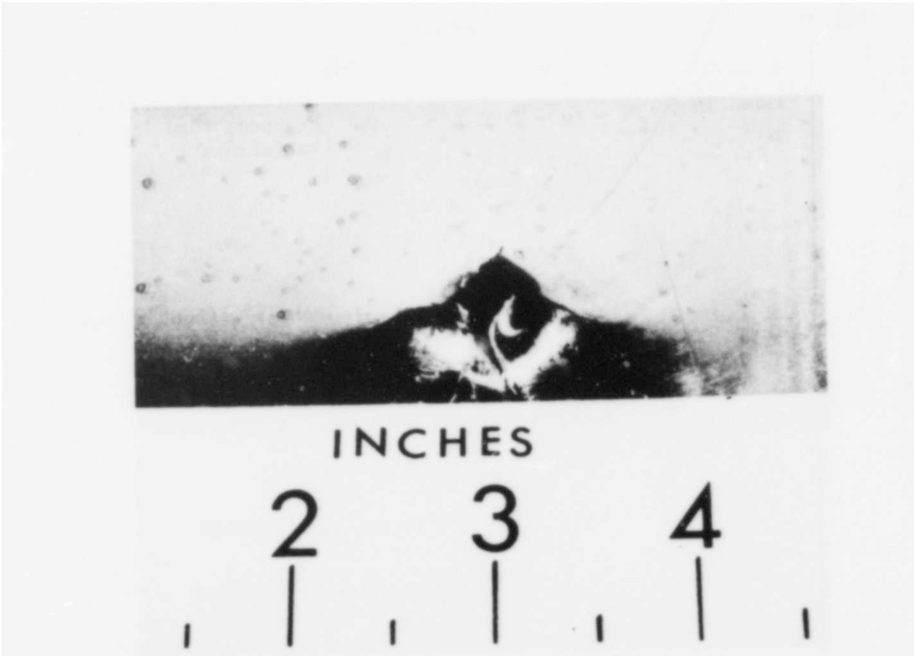


Figure 5. Typical Crack Made by Impacting a Pointed 0.375-Inch-Diameter Rod in an Unstressed 12-Inch by 0.032-Inch 7075-T6 Aluminum Panel.

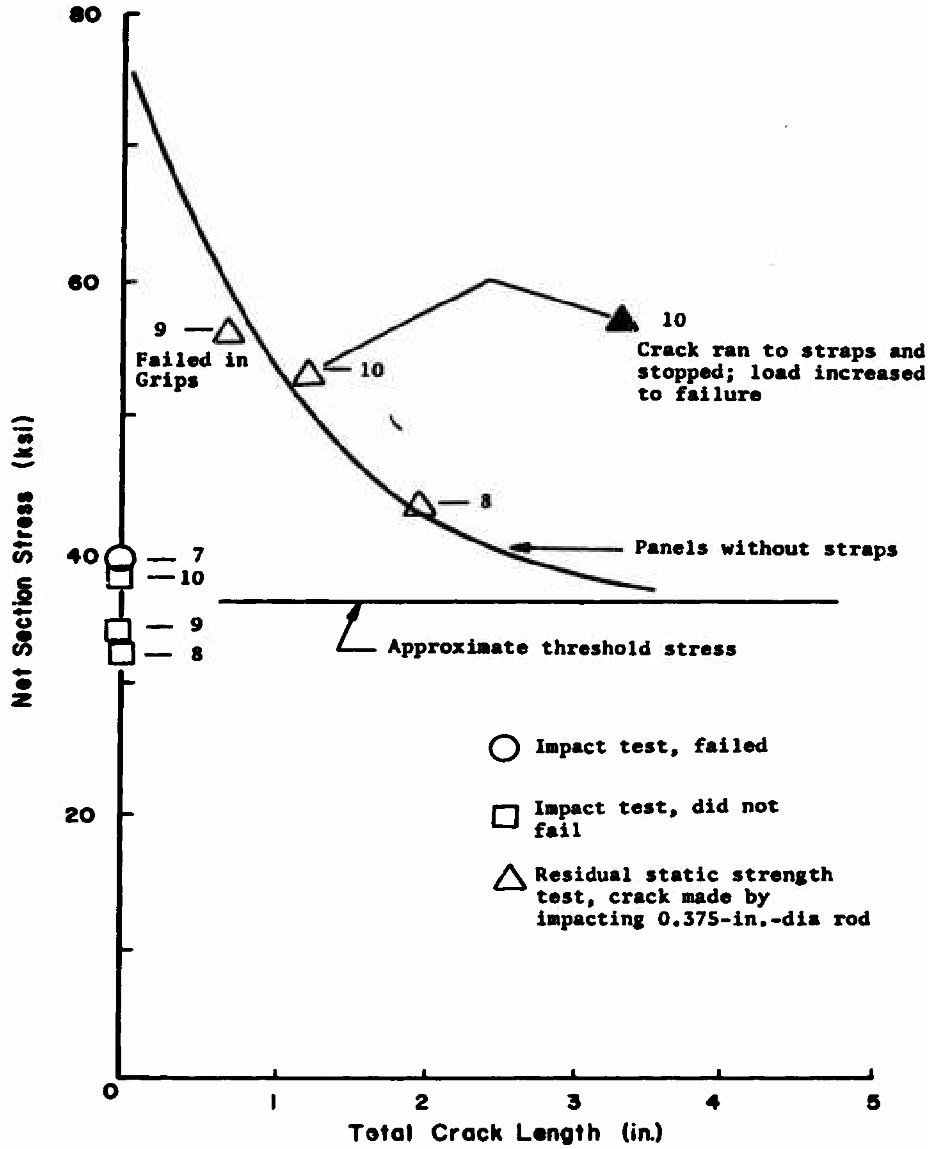


Figure 6. Crack Arrest and Residual Static Strength of 12-Inch by 0.032-Inch 7075-T6 Clad Panels With Straps.

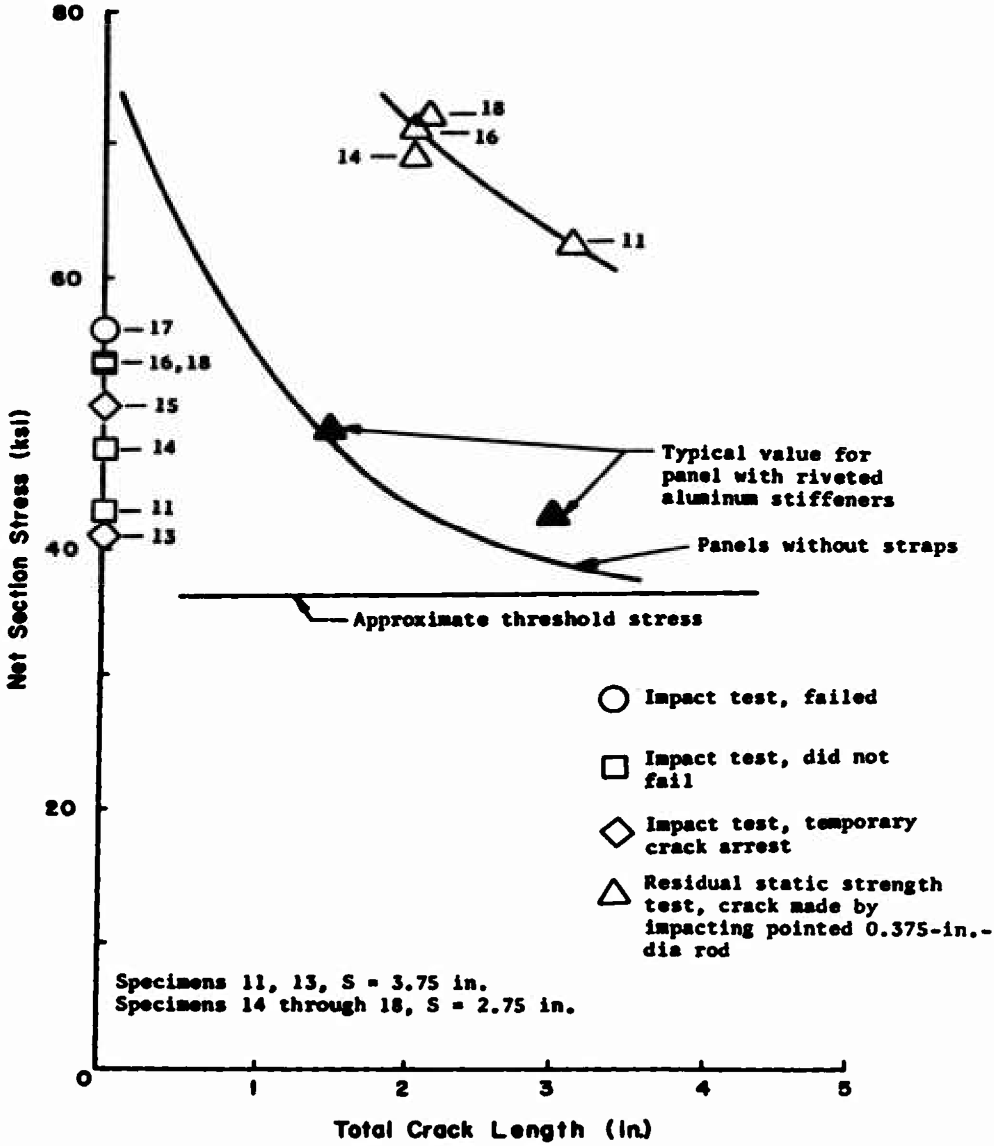


Figure 7. Crack Arrest and Residual Static Strength of 12-Inch by 0.032-Inch 7075-T6 Bare Panels, Two Straps on Front and Back Sides of Specimen.

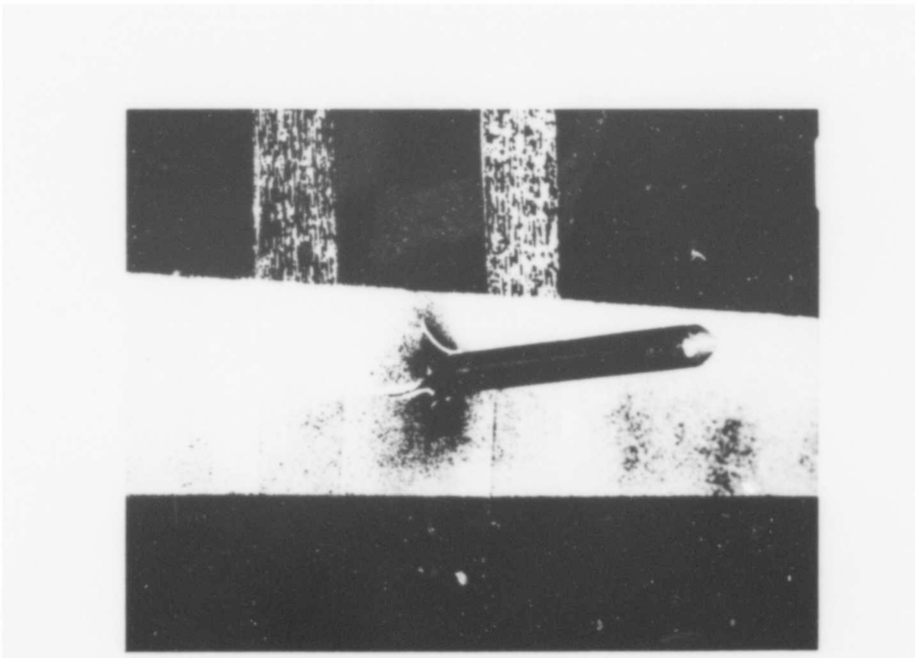


Figure 8. Typical Crack Arrest Behavior of 7075-T6 Bare Panels With Two 0.75-Inch by 0.010-Inch 1002-S Fiberglass Straps on Front and Back Sides of Specimen; Strap Spacing, Centerline to Centerline = 2.75 Inches.

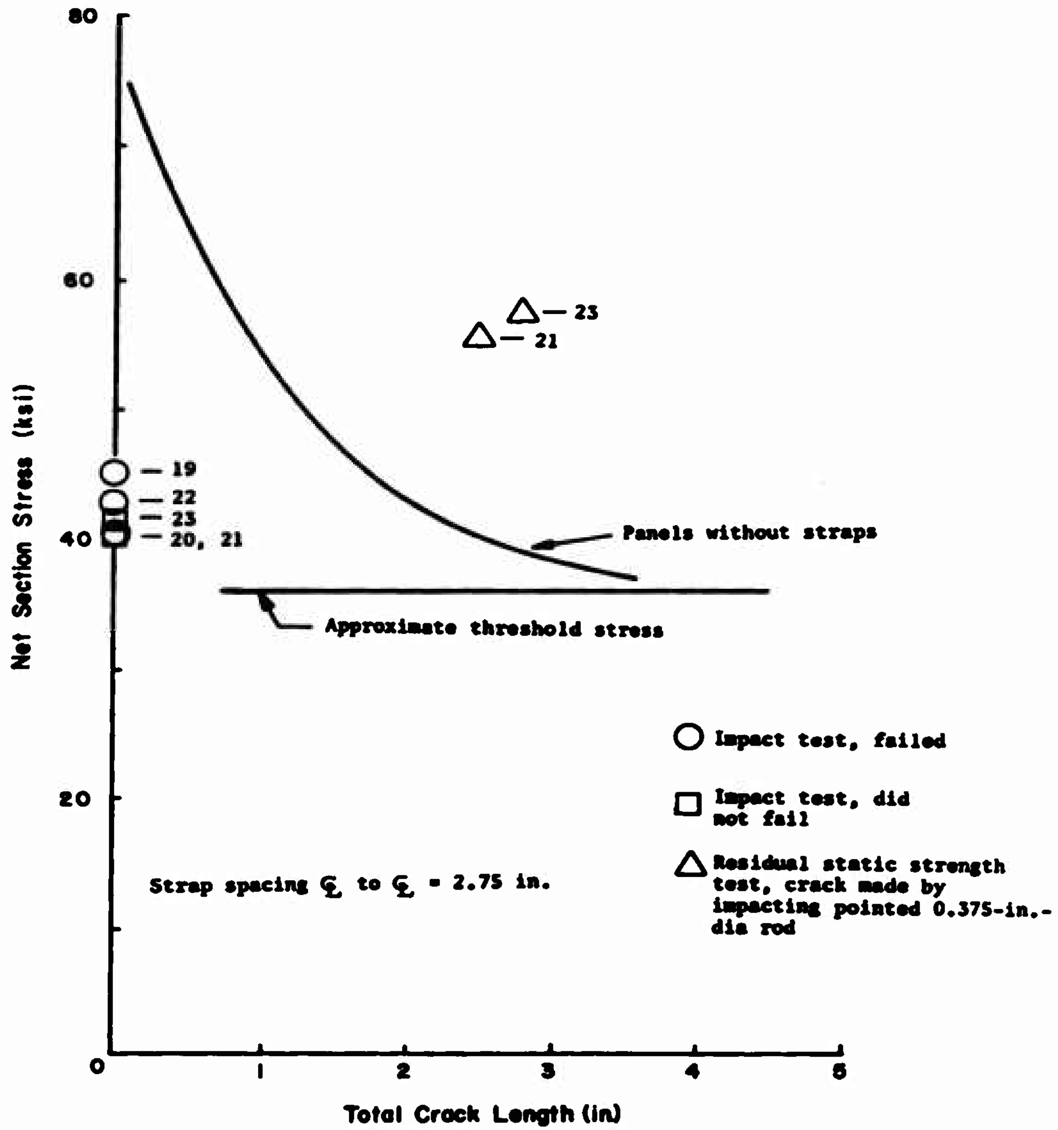


Figure 9. Crack Arrest and Residual Static Strength of 12-Inch by 0.032-Inch 7075-T6 Bare Panels, Two 0.75-Inch by 0.010-Inch 1002-S Fiberglass Straps on Impact Side of Specimen.

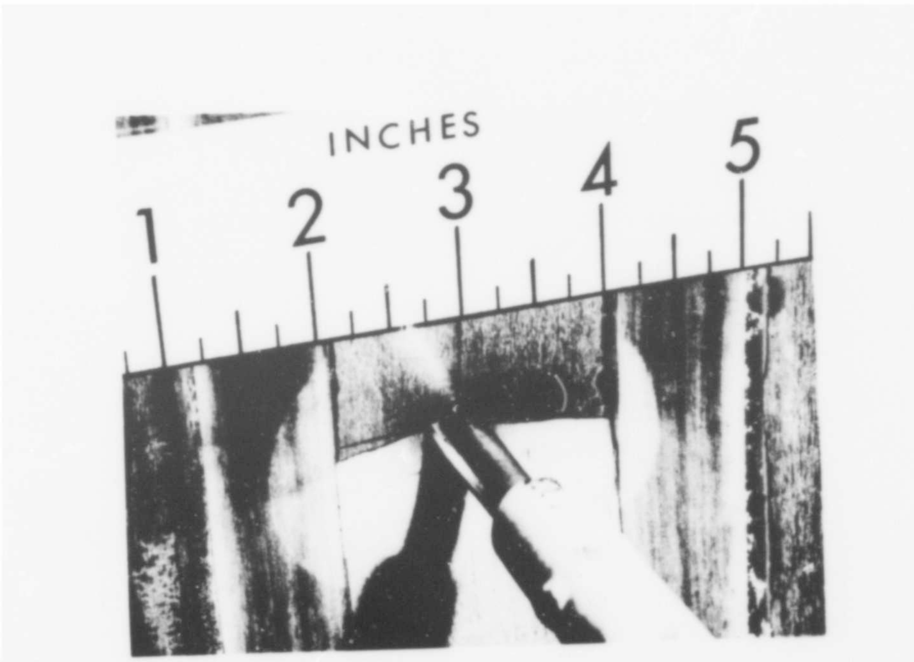


Figure 10. Typical Crack Arrest Behavior of 7075-T6 Bare Panels With Two 0.75-Inch by 0.010-Inch 1002-S Fiberglass Straps on Impact Side of Specimen.

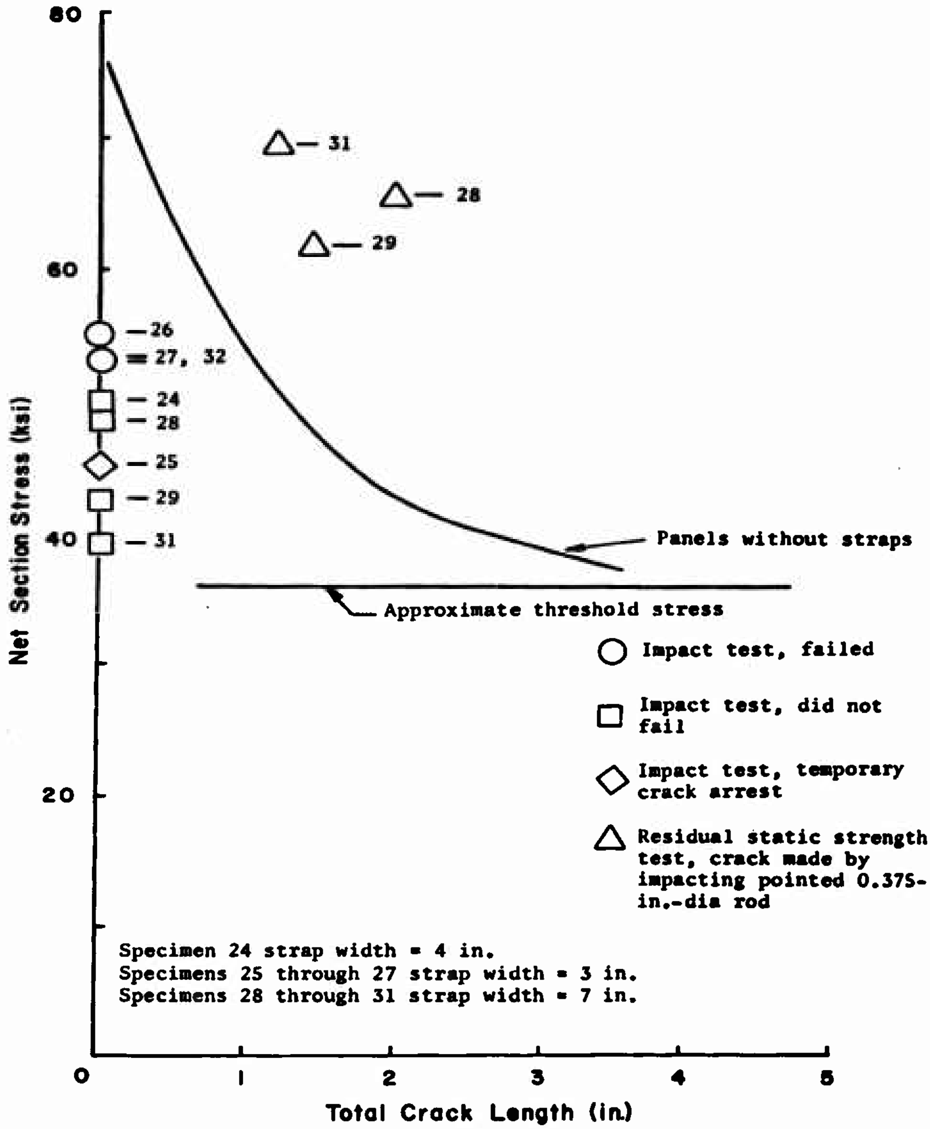


Figure 11. Crack Arrest and Residual Static Strength of 12-Inch by 0.032-Inch 7075-T6 Bare Panels, One Strap on Impact Side of Specimen.

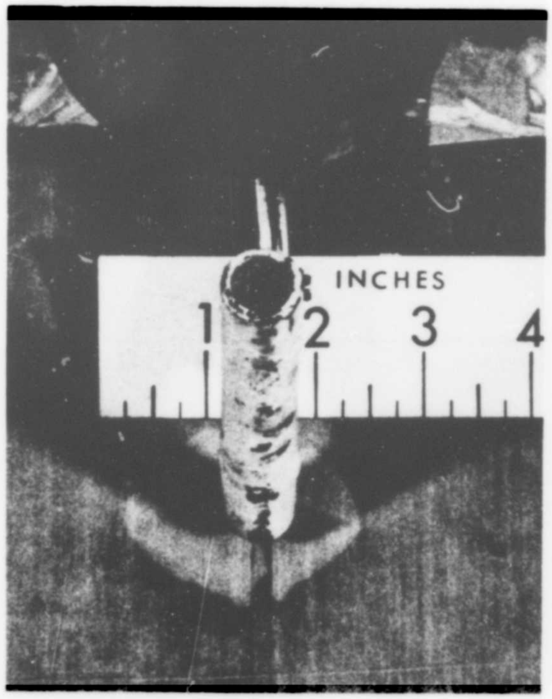


Figure 12. Typical Crack Arrest Behavior of 7075-T6 Bare Panels With One 7-Inch by 0.010-Inch 1002-S Fiberglass Strap on Impact Side of Specimen.

Loading Direction

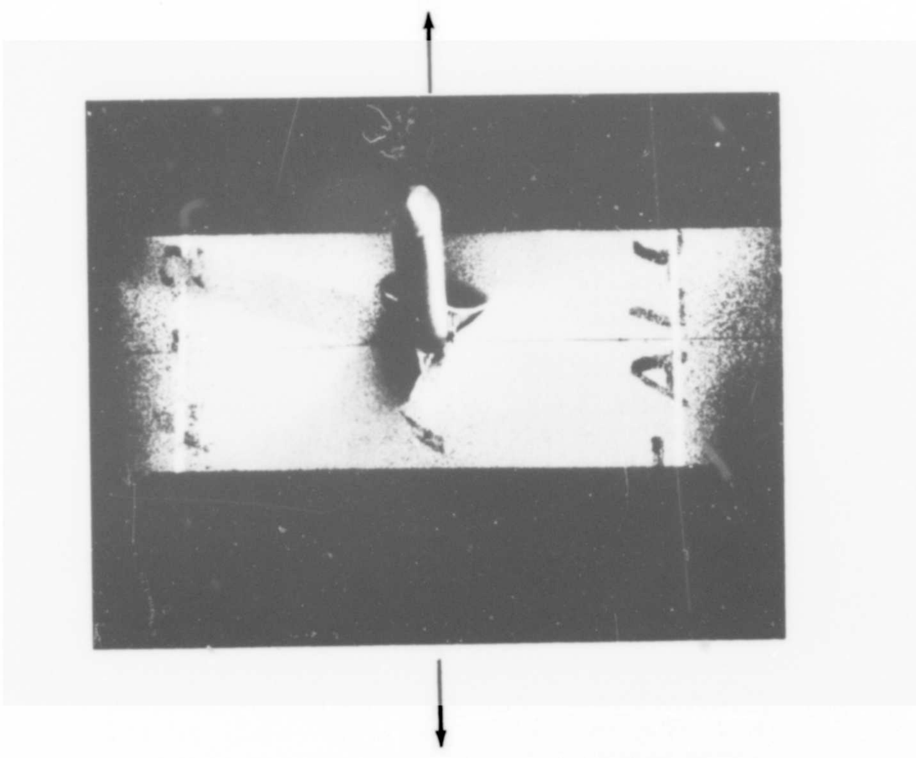


Figure 13. Crack Arrest Behavior of a 12-Inch by 0.032-Inch 7075-T6 Bare Panel With One 4-Inch by 0.010-Inch Fiberglass Strap on Impact Side of Specimen.

SUMMARY

The test results may be summarized as follows:

1. Significant increases in both crack arrest and residual static strength behavior were obtained with thin straps of 1002-S fiberglass bonded to the panels. Table III summarizes the improvements over panels without straps.

TABLE III. SUMMARY OF CRACK ARREST AND RESIDUAL STATIC STRENGTH BEHAVIOR OF MATERIALS TESTED

Configuration (1002-S Fiberglass Straps)	Improvement in Crack Arrest (%)	Improvement in Residual Static Strength (%)
Two 0.75-in. by 0.010-in. straps, front and back sides of specimen, centerline to centerline spacing 2.75 in.	48	70
Two 0.75-in. by 0.010-in. straps, front and back sides of specimen, centerline to centerline spacing 3.75 in.	15	63
Two 0.75-in. by 0.010-in. straps, impact side of specimen, centerline to centerline spacing 2.75 in.	15	46
One 3-in. by 0.010-in. strap, impact side of specimen	19	14, Est
One 4-in. by 0.010-in. strap, impact side of specimen	39	NA
One 7-in. by 0.010-in. strap, impact side of specimen	39	33

2. Running cracks in 7075-T6 panels were arrested by thin straps of fiberglass tape bonded to the panels.

3. Residual static strength values (71.4 ksi) approaching the ultimate tensile strength (77.3 ksi) for a 12-inch by 0.032-inch panel containing a 2-inch-long crack were achieved by placing two 0.75-inch by 0.010-inch 1002-S fiberglass straps on the front and back sides of the specimen. Centerline to centerline spacing for these straps was 2.75 inches.

4. Proper specimen cleaning and preparation were required to ensure a satisfactory bond and close proximity between the fiberglass straps and the aluminum panels.

ADDITIONAL WORK

Additional work is needed to achieve a method of applying straps that does not require extensive surface preparation and that permits a cure without pressure and heat. Also, additional work is needed to evaluate the behavior of the straps after being subjected to service loadings and environmental conditions.

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13. ABSTRACT

Crack arrest and residual static strength tests were conducted on 12-inch-wide bare and clad 7075-T6 aluminum alloy specimens to determine the effects of thin straps of fiberglass tape bonded to the specimens. Specimens were preloaded in a close-loop hydraulic test machine, a pointed 0.375-inch-diameter rod was driven through their midpoint, and their crack arrest and residual static strength behavior was observed with high-speed photography. Various configurations were studied, including those with one strap bonded to one side of the specimen and those with two straps bonded to either one or both sides of the specimen. The tests indicated that running cracks can be arrested by the fiberglass straps. Significant increases in the crack arrest behavior of up to 48 percent were obtained with two 0.75-inch by 0.010-inch straps spaced 2.75 inches apart on the front and back sides of the specimen. Residual static strength values (for a specimen with a 2-inch-long crack) approaching the ultimate tensile strength of the material were achieved by this method.

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Ballistic Tolerance						
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